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CCS Chain Capacity Selection for Flexible Load Power Plant

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Abstract

Coupling flexible power generation with Carbon Capture and Sequestration (CCS) technology may be important for substantial reductions in CO_2 emissions. In this paper we consider some of the implications of flexible power plant operation on the CCS process. Specifically, we consider the CCS chain capacity selection decision, by which we mean the choice of the optimal plant size, to understand what determines the amount of CO_2 that is efficient to capture and how the decision to invest in CCS chain capacity is affected by price volatility of CO_2 emissions quotas. We found that the plant's emissions profile determined a range of CCS capacities that could be efficient with the tradeoff between the price of CO_2 emissions quotas and the cost of CCS technology determining the specific optimal chain capacity. Secondly, investment into CCS technology for a flexible load power plant was more likely to be delayed in a multiple time point investment decision tree model as a result of price volatility, compared to investment in CCS technology on a base load power plant.

Keywords: flexible power, CCS, investment decision, CO_2,capacity

1. Introduction

The potential of CCS technology to facilitate the transition to a low carbon economy has been widely acknowledged, although as pointed by IEA GHG in 2009, little research has been done on CCS application beyond base power load provision [1]. Base load power however provides 30-40% of the total power load in many systems, and it is likely that CCS technology will need to be applied for intermediate and peak power load generation to achieve substantial reductions in CO_2 emissions [1]. Meeting this variable power demand requires development of CCS plants capable of flexible operation [2]. Flexible power generation with CCS is possible, particularly with post combustion capture, which allows CO_2

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capture to be turned on and off to provide operational flexibility [3]. With a flexible load plant however, the decision of how much CO_2 to capture becomes important, since the flow of CO_2 emissions may vary daily and seasonally, and investors face the trade-off between capturing CO_2 and paying for emissions. In our study we analyze this trade off, discussing factors that influence the investment into CCS chain capacity with base load and flexible load plants. We also use a multiple time point, investment decision tree model developed by Celebi and Graves [4] to study the delay in investment that can result from high price volatility for emissions quotas, comparing scenarios where a retrofit installation of CCS technology is being considered for base load and flexible load plants, to determine the sensitivity of each case to price volatility.

2. Methods

Two case studies are presented in this paper. The first case addresses the issue of optimal CCS chain capacity selection under flexible power plant operation. The case is based on an investment scenario with no price uncertainty and an irreversible investment decision. In the second case we analyze the timing of the investment decision into CCS technology for a base load and flexible operation power plants, and the possible delay in investment that can occur due to price volatility of CO_2 emissions quotas (CO_2 quotas). CO_2 quota price uncertainty, and timing of the investment decision, is introduced in this study using a decision tree model.

2.1. Case 1: Optimal CCS chain capacity: a now or never decision under zero CO_2 price uncertainty

In this case study we contrast the optimal CCS chain capacity choice between base load and flexible load power plants considering no uncertainty in the price of CO_2 quotas. One of the fundamental differences between the two types of plants is that one generates power and CO_2 emissions at a constant rate, while the flexible load plant varies in power and consequently emissions outputs, potentially changing its load between seasons and times of day. For the purpose of simplicity, we assume an emissions profile that varies by month for the flexible load plant. Although at this time step the profile better resembles semi base load operation, in the context of this model we refer to it as flexible operation.

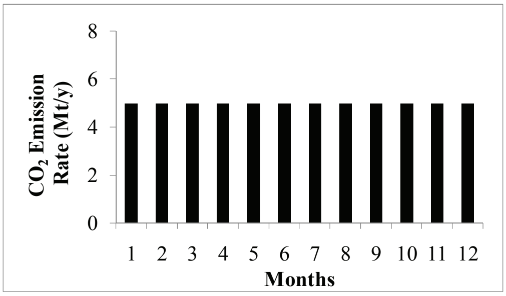

Figure 1a: Base Load Plant Emissions Profile, Case 1a

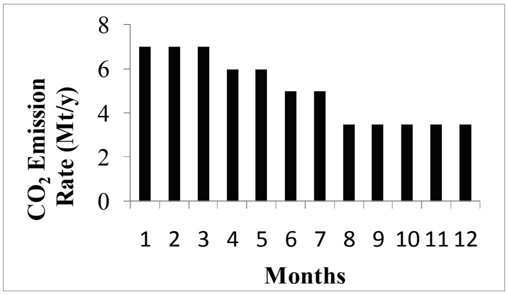

Figure 1b: Flexible Load Plant Emissions Profile, Case 1b

Case 1a: CCS Chain Capacity Choice for Base Load Power Plant

In the base case, it is assumed that a base load power plant is in existence in year 2020, and will continue to operate until 2055 emitting CO_2 at a constant rate of $5MtCO_2/y$ (Figure 1a). The owner must mitigate his emissions starting in 2020 either through paying for emissions quotas, or by capturing and storing the CO_2. In this first case, under assumption of zero CO_2 quota price volatility over the project life span, the plant owner must choose in year 2020 whether to pay emissions quotas until 2055 or to invest in

CCS technology. If the owner invests, he must decide how much CO_2 it is economical to capture. Upon investing, the plant owner must pay taxes on full emissions for the first three years after the investment is made to simulate capacity construction, after which he only pays for residual CO_2 emissions not captured (90% capture rate, see section 2.2).

Case 1b: CCS Chain Capacity Choice for a Flexible Load Power Plant
Assumptions are the same as in Case 1a, except the CO_2 emitting power plant is now a flexible load plant, and produces variable amounts of electricity and CO_2 emissions throughout the year. Annual emissions remain at 5MtCO_2/y, but the monthly emissions rate varies between 3.5 MtCO_2/y and 7MtCO_2/y, making the selection of a CCS chain capacity more complicated (Figure 1b). We analyze the CCS chain capacity investment decision in the context of some of the economic variables that impact the capacity decision, namely the price of CO_2 quotas, the plant emissions profile and the costs of CO_2 capture, transport and storage. A price of € 35/tonCO_2 was assumed for calculations of emission costs. It is difficult to pick a unique CO_2 price given the range of current estimates for break-even prices. For demonstration project in the near term, 40-90 €/ton are the accepted range [5,6,7] while from 2030 onwards, break-even prices may decline to €/ton 30-45 [5,7]. We assume a lower bound estimate for the 2020-2055 as a result of technological learning and experience.

2.2. Case 2: Effect of price volatility on investment in CCS

In case 2 we contrast the effect of price volatility of CO_2 quotas on the decision to invest in CCS technology on an existing base load and flexible load power plants. The comparison is developed by using a multiple time point investment decision tree model, with a stochastic price distribution, where the investment decision is irreversible. The model is based on a stochastic price distribution and is solved through reverse induction. The model shows how price variability can delay investment into CCS technology and is adapted from a discussion paper by Celebi and Graves [4].

Case 2a: Base Load Power Plant
In the case framework, the owner of an existing base load power plant that emits 5 MtCO_2/y, must mitigate the plant's CO_2 emissions. In 2020, he has the option to purchase emissions quotas or invest in CCS technology on a plant that will produce CO_2 until 2055. Purchasing quotas allows the owner to wait for more information on CO_2 price development before making an irreversible investment decision in CCS technology. This is a contrast to case 1 where the decision to invest in CCS or pay for emissions quotas in 2020 was irreversible. In this case the owner can make a decision of whether to invest in CCS technology or pay emissions quotas at three time points separated by 5 year intervals beginning in 2020: 2020, 2025 and 2030. The price of CO_2 quotas varies through a simple stochastic process between the time points with equal probability of remaining the same, increasing, or decreasing to the extent given by price volatility, which is one of the model parameters. If the owner chooses to invest, he must purchase emissions quotas for 3 years for full plant emissions while CCS capacity is installed. Afterwards, he pays for CO_2 quotas only on residual CO_2 emissions not captured. The price of CO_2 quotas will be locked in the year an investment decision is made and will remain the same for the project's economic life. Under this assumption, and the symmetric CO_2 price probability distribution, the expected future price of CO_2 is equal to the price at the time of investment. Alternatively, the owner can choose to wait until the next period, and pay for 5 years of CO_2 quotas on plant emissions at the CO_2 price observed in the beginning of the period. Year 2030 is the last opportunity for a decision, where the plant owner must choose to either invest in CCS or pay quotas on full emissions at the 2030 CO_2 price for the remainder of the plant's economic lifetime.

Model output shows the expected net present value of costs for mitigating CO_2 at each of the decision time points. This allows for prediction of when an investor will wait and pay emissions quotas or invest in CCS technology by comparing the cost of investing at that time point to the cost of waiting and making the investment decision at a later time. A sensitivity analysis is also performed over a range of CO_2 quota price volatilities from 60% to 10% over 5 years. This shows the effect of quota price volatility on the investment decision. Figure 2 illustrates the timeline of the plant owner's decision, showing high (60%) and low (20%) volatility price scenarios. These volatilities represent CO_2 quota price uncertainty over 5 year periods. In annual terms, the high and low price volatilities are 27% and 9% respectively. The low price volatility scenario in this case is very low, and represents high price stability for CO_2 quotas. The model is solved through reverse induction, starting at the 2030 decision tree nodes and back calculating based on optimal decisions. In this way, the average cost of mitigating emissions in 2030 for each branch of the decision tree, is discounted back to 2025 with addition of 5 years of emission costs, and represents the expected cost of waiting and making the investment decision later. The same process is applied to 2025 costs to determine the value of the "invest later" option with respect to 2020.

Case 2b: Flexible Load Power Plant Case

In the flexible load power plant scenario, annual emissions remain the same at 5 $MtCO_2/y$ but the monthly emission schedule varies to resemble seasonal power generation (Figure 1 b). While in the base load power plant case the decision being modelled was whether to invest and mitigate 90% of emissions or wait, an additional parameter is added here: the choice of CCS chain capacity in which to invest. Given the variable emissions profile presented in Figure 1b, the plant owner must choose a CCS chain capacity for his power plant that minimizes the cost of CO_2 mitigation. This results in a trade off between payment for CCS technology and payment for emissions quotas. Building the CCS chain capacity to capture all annual emissions results in unutilized capture capacity for some of the months, while building less capacity results in greater payments for emissions quotas. All other model assumptions remain the same as in the base case. The effect of price variability on base load (Case 2a) and flexible load plant (Case 2b) investment outcomes is compared in section 3.3.

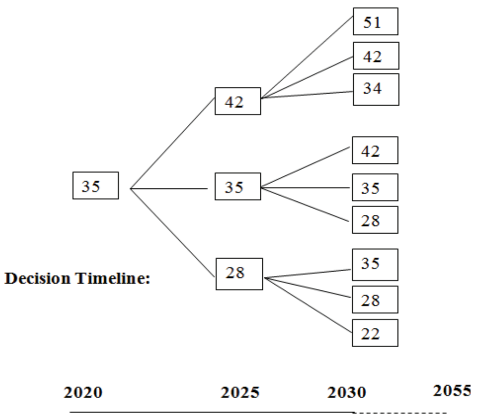

Figure 2a: Low price variability scenario. 20% over 5 years

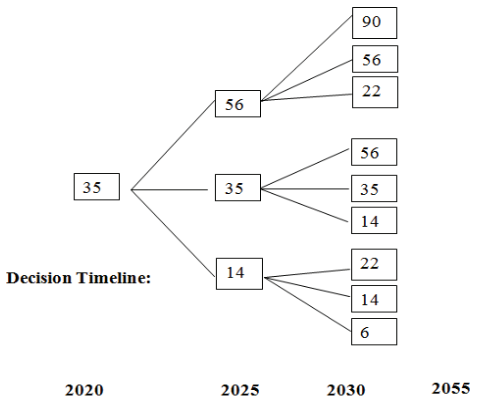

Figure 2b: High price variability scenario. 60% over 5 years

2.3. CCS Assumptions and Costs:

Amine post combustion capture process with 90% capture efficiency, based on a chemical solvent Monoethanolamine (MEA) was utilized in this study. The investment and operating costs for CCS at different capacities were derived from a 2 $MtCO_2/y$ post-combustion CCS plant simulation carried out in

Aspen Process Economic Analyzer® and subsequent scaling using the equipment cost power law and installation factors for the 1-7 $MtCO_2$/y capacities used in this study. It was assumed the CCS plant received a flue gas with a 13% concentration of CO_2, which is similar to conventional coal fired power plants.

2.4. Capture costs

The operating cost is split into fixed and variable operating costs. The fixed operating cost depends on the total investment cost, and covers maintenance, insurance and labour costs. The variable operating cost is a function of the operation load and CO_2 quantities captured. It covers consumption of utilities, electricity, steam, cooling water and MEA make up. Variable costs are assumed to be linear down to 1 $MtCO_2$/y CCS chain capacity due to parallel construction of main utility consuming units, such as blowers, the stripper and cooler. When a plant doesn't operate at full capacities, some of the parallel units are shut down while the rest operate at full capacity. Therefore it can be assumed that there is no efficiency decreases when a plant doesn't operate at full capacity. However it is assumed that a plant cannot operate under 0.6 Mt/y otherwise the operating condition of the packed columns is overly perturbed. The annual fixed operating cost is assumed to be 7% of total investment costs, while the annual variable operating cost are estimated using the utilities consumptions given by process simulations and utility costs shown in Table 1. It is worth noting that the steam cost presented in Table 1 is based on extracting steam from the LP steam circuit. Table 2 shows the functions used to derive Capital, Fixed Operating, and Variable Operating costs.

Table 1: Utilities costs

Utilities	Costs	Units
Electricity	55	€/MWh
Steam prior to LP turbine (5bar 150°C)	3.5	€/GJ
Water	0.02	€/m^3
Pure MEA	1300	€/t

Table 2: Cost functions for capture process

Function	Costs	Units (y)
y = 58.45x* + 15.24	Capital	(€) Million
y = 4.091x* + 1.067	Fixed Operating	(€)Million/y
y = 15.26x*	Variable Operating	(€) Million/y

*x is the CCS chain capacity, ranging from 1-7 $MtCO_2$

2.5. Transport and Storage Costs

With respect to transport and storage, an 80 km pipeline length was assumed with cost functions, and pipeline diameter guidelines taken from a US National Energy Labs report [8] to estimate transport and storage costs. Table 3, based on the emission profile in Figure 1b, summarizes those costs together with pipeline diameters used for the flexible load power plant case.

Table 3: CAPEX, fixed and variable OPEX for CO_2 transport and storage for flexible load power plant.

Annual CCS Capacity (Mt CO_2/y)	1	2	3	4	5	6	7
Pipeline Diameter (cm)	20	28	36	38	41	43	46
CAPEX (Million €)	43.4	57.9	73.2	85.2	97.1	109	121
Fixed OPEX (Million €/y)	0.44	0.44	0.45	0.45	0.45	0.45	0.47
Variable OPEX (Million €/y)	0.02	0.04	0.06	0.07	0.09	0.11	0.13

3. Results and Discussion

3.1. Optimal CCS Chain Capacity Choice: Case 1a and 1b

For discussion of CCS chain capacity selection, unit costs for CCS were calculated in €/tonCO_2 to compare the investment costs between different CCS chain capacities (Figure 3a-3b). Costs for CCS were subdivided into several components: fixed and variable operating costs and capital costs of CCS plant, as well as the costs of emissions quota payments (Figure 4). Additionally, in order to analyze the costs and benefits of a given CCS chain capacity, savings in unit costs of CCS were calculated for each 1Mt/y increase in CCS chain capacity (Figure 5). Savings in the cost of CCS were achieved when the cost of mitigating CO_2 emissions declined as a result of an increase in CCS chain capacity. More specifically, that means the decrease in emission payments as a result of additional CCS chain capacity was greater than the cost of the CCS technology. Unit costs of CCS across different CCS capacities and a range of CO_2 quota prices are presented in Figures 3a and 3b for the base load and flexible load power plants. These costs were modelled to demonstrate how the optimal CCS chain capacity choice can change with the price of CO_2 quotas.

With the base load plant that maintains a constant rate of emissions of 5 Mt/y (Figure 1a) it is optimal to invest in 5 Mt/y of CCS chain capacity (Figure 3a), or to not invest at all if prices are too low, and just pay emissions quotas. A detailed breakdown of costs in Figure 4 helps to understand why this is the case. It is apparent that as the CCS chain capacity increases, the fixed operating, capital, and variable costs associated with the technology also increase.

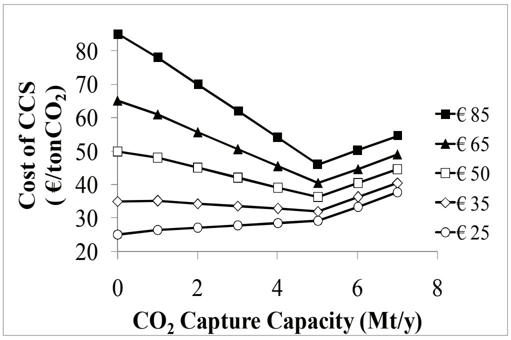

Figure 3a: Case 1a, unit costs for CCS with base load plant at different CO_2 prices

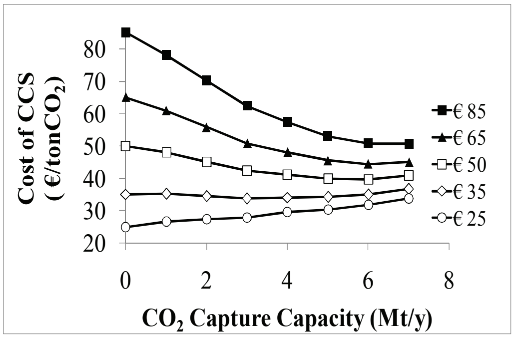

Figure 3b: Case 1b, unit costs for CCS with flexible load plant at different CO_2 prices

This increase is offset by declining costs of CO_2 quotas and it is efficient to keep adding more CCS chain capacity so long as the decline in CO_2 quota costs is greater than increases in technology (CCS) costs. Beyond 5Mt/y, additional capacity expansion does not reduce costs, only increases them independent of CO_2 quota price. From this it follows that the owner of a base load plant that emits at a rate of 5MtCO_2/y will always install 5Mt/y of CCS chain capacity, so long as the CO_2 price is sufficiently high, because the marginal cost of adding additional capacity up to 5Mt/y will be less than the marginal benefit. With the flexible load plant, more outcomes are possible (Figure 3b). Unit costs for CCS in Figure 3b show that a CCS chain capacity of 3MtCO_2/y is the most efficient solution when CO_2 quota prices are around €35/ton, a capacity of 5 MtCO_2/y is best at higher CO_2 quota prices of around €50/ton, and at very high CO_2 quota prices, a capacity of 6 MtCO_2/y is most efficient. Even though the annual amount of CO_2 produced is 5Mt/y, peak CO_2 flows in the flexible load power plant emission profile exceed that for some of the year. That makes a higher CCS chain capacity choice efficient only at high

CO_2 quota prices (Figure 1b). These optimal CCS chain capacity outcomes at different CO_2 quota prices closely follow the steps in the emission profile, which are 3.5, 5, 6 and 7 $MtCO_2$/y (Figure 1b), suggesting that the emission profile in particular dictates what capacities can be economical. A CCS chain capacity that does not match a rate of emissions necessarily results in either inefficiently too little CCS capacity, with costly payments for CO_2 emissions, or with too much capacity, which results in capacity underutilization and inefficiently high technology costs. The trade off between the price of CO_2 and the cost of CCS technology then specifies which of the efficient CCS chain capacities will be optimal.

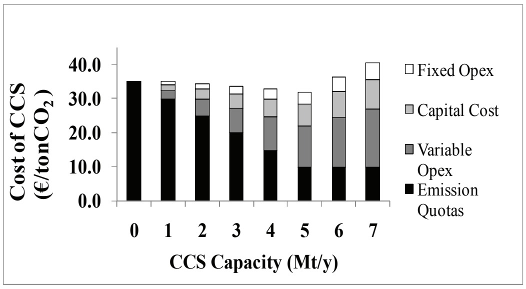

Figure 4: Cost break down for base load plant case at CO_2 price of €35/ton.

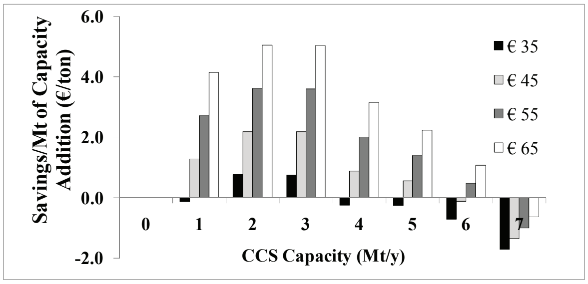

Figure 5: Savings in per unit costs of CCS from chain capacity addition at different CO_2 prices, for flexible load plant.

Figure 5 illustrates this trade off, showing the marginal savings in unit cost of CCS from additional CCS chain capacity for the flexible load power plant. Savings are shown at different CO_2 quota prices, with positive bars indicating positive savings and the decline in unit cost of CCS due to capacity expansion, while negative bars represent increases in unit costs of CCS, indicating that additional capacity should not be built. Figure 5 demonstrates two important aspects of the trade off between additional CCS chain capacity and emissions quota payments: greater savings from additional capacity at higher CO_2 quota prices and a declining rate of savings in unit costs of CCS with increasing capacity. The first point means that as CO_2 quota prices increase, the cost of paying emissions quotas becomes very large and investing in CCS technology becomes cheaper than paying for quotas. The higher the price of emissions quotas, the greater the savings realized from investing in CCS. The second point is less intuitive: declining savings from additional CCS chain capacity result from the shape of the emission profile. Highest savings are achieved from adding the first 3 Mt/y of CCS chain capacity, while additional capacity brings lower savings. This is a result of the emission profile (Figure 2b), where the 3.5 $MtCO_2$/y emission rate occurs for the longest time period. Because fewer emissions occur at other rates, reductions in cost above the 3.5 Mt/y CCS chain capacity are also smaller. For this reason, even though the 7 $MtCO_2$/y emission rate is part of the emission profile, it is not economical to add this capacity under the CO_2 quota prices we consider. The cost of adding the additional CCS chain capacity is greater than savings on emissions. It is more efficient to pay for the additional emissions. Investors with limited capital could therefore potentially increase return on investment by spreading CCS investment on multiple smaller CCS installations on power plants with flexible load, rather than one single large capacity CCS installation.

3.2. *Case 2a: Base Load Power, Plant Investment and Price Volatility*

Investment outcomes for the base load power plant case 2a are presented with high and low CO_2 quota price volatility scenarios. Like Celebi and Graves [4] we find that high emissions quota price volatility, delayed investment in CCS technology by at least 5 to 10 years (Figure 6). Figure 6 explains this result, showing information nodes which contain CO_2 quota prices as circles, the decision to wait and pay emissions quotas as a dotted square, and the irreversible investment decision into CCS technology as a solid square. Asterisks mark the best alternative at each information node between waiting and investing. Seeing high emissions quota price uncertainty, with future CO_2 quota prices ranging from € 5.5 - € 90/ton CO_2, the plant owner chooses to wait and pay emissions quotas from 2020 to 2025, because the expected cost of mitigating CO_2 emissions is lower in the future as a result of high price volatility.

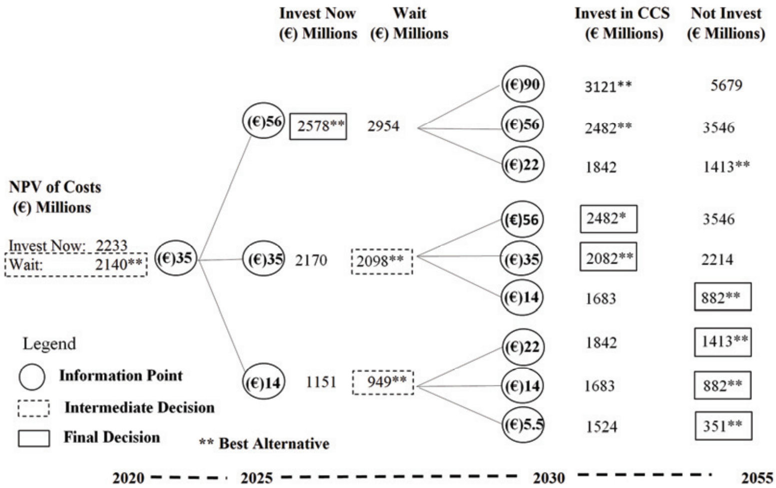

Figure 6: Base load plant CCS investment scenario with high price variability

The expected savings from exercising the option to invest at a later time is € 93 million, which is the difference between the cost of investing now, and the expected cost of waiting and making the decision later. We call this the expected value of waiting and it can be positive and negative. When it is positive, the plant owner is better off waiting for more information and making the investment decision later. If the expected value of waiting is negative, then the cost of waiting is greater than investing, and it is better to invest. After the 2020 decision to wait, if high CO_2 quota prices are observed in 2025 the owner chooses to invest, while if the same or lower CO_2 quota prices are observed as in 2020, the owner pays emissions quotas and waits. In 2030, at higher CO_2 quota prices the plant owner chooses to invest in CCS, but decides to pay for CO_2 quotas if quota prices are low. Ultimately we see that a high uncertainty in prices creates incentives to delay investment. In Figure 6, the model cannot predict what outcome will occur, it only shows a range of possible outcomes and the potential delay in investment that can result. In the case of relatively stable CO_2 quota prices, with volatility of 20% over 5 years, the low CO_2 quota price outcomes that motivate the decision to delay investment are no longer possible. As a result there is no incentive to delay investment. The expected value of waiting is now negative, and it is better to invest in CCS technology in 2020 because the expected cost of waiting in 2020 is € 83 million greater than investing.

3.3. Case 2b: Flexible Load Power Plant, Investment and CO_2 Quota Price Volatility

As with the base load power plant, uncertainty in the price of CO_2 emissions quotas results in delay of investment of 5-10 years, but more importantly, the investor now faces uncertainty in CCS chain capacity choice. As discussed previously, the emission profile determines which capacities can be efficient, while the trade off between the price of CO_2 quotas and the cost of technology determines the optimal CCS chain capacity. Figure 7 shows a high price variability scenario for the flexible load power plant. The cost of waiting and investing is no longer shown, rather the optimal capacities that would be chosen at each price are displayed. The CCS chain capacity choices that result, given the high CO_2 quota price volatility scenario, are 0, 3 Mt/y, 6 Mt/y and 7 Mt/y (Figure 7). According to our model, other capacities, such as 1, 2, 4 and 5 Mt/y can still be built, but it would not be cost efficient to do so. In this high emissions quota price volatility scenario (Figure 7), the plant owner would choose to delay investment in 2020 because of the high uncertainty in future CO_2 quota prices. In 2025, if CO_2 quota prices are high, the plant owner invests in 6Mt/y of CCS chain capacity, otherwise he waits. In 2030, he invests in either 3 or 6 Mt/y of CCS chain capacity if CO_2 quota prices remain the same or increase, otherwise he chooses to pay for emissions if CO_2 quota prices remain low. It is notable that while the maximum optimal CCS chain capacity that the plant owner invests in within this scenario is 6 Mt/y, the peak CO_2 flow rate for the flexible load plant is 7 Mt CO_2/y. Very high emissions quota prices of around €90/tonCO_2 are required to make this an optimal CCS chain capacity choice since emissions at this rate are only observed for 3 out of 12 months of plant operation.

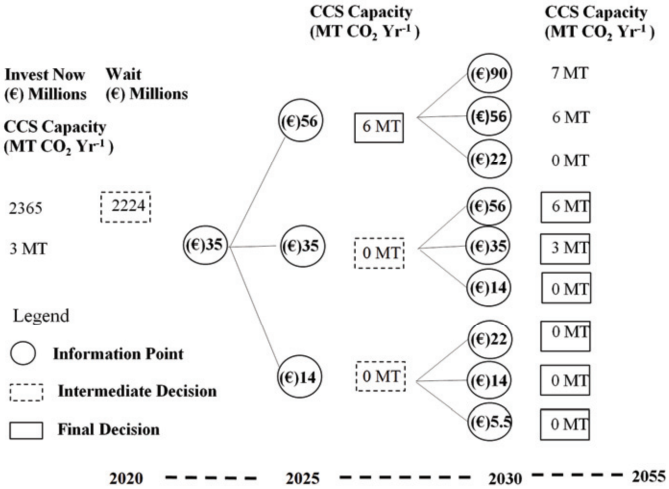

Figure 7: Flexible Load Power Plant, High Price Volatility

At lower CO_2 quota prices, the cost of the CCS technology would be greater than purchasing emissions quotas for this amount of CO_2. This outcome, where not all of the CO_2 is captured may be common to variable emissions plants, especially those with large fluctuations in emissions. Owners of such plants will pay more for emissions quotas compared to the base load power plant scenario. This has important implications for the investment outcome. Since the plant owner pays more for emissions in the case of a flexible load plant, changes in CO_2 quota prices have a greater effect on the NPV of costs for CO_2 mitigation than in the base load power plant case. Not only is the NPV of costs for CO_2 mitigation greater for a flexible load plant as a result (Figure 7), but in a high price volatility scenario that means there is a greater incentive to wait and delay investment to watch how CO_2 prices develop. For the flexible load plant, the expected cost of mitigating CO_2 emissions after 2020 is € 141 million less than investing into CCS capacity in 2020. This means it is better to wait before deciding whether to invest in CCS, and the value to waiting is 50% greater than for the base load plant case, where it is € 93 million (Figure 6). This is a result of the uncertainty in future CO_2 quota prices which substantially change how much the plant owner will pay for emissions quotas. In the low price volatility case, as with the base load power plant, it is optimal to invest right away in year 2020 and the optimal CCS chain capacity choice is 3 Mt/y. At the CO_2 quota price of € 35/ton, it is optimal to only capture some of the emissions, and pay emissions quotas on the rest.

Figure 8a plots the comparison in the "Expected Value of Waiting" between base load and flexible load plant scenarios to compare the effect of CO_2 quota price volatility on the decision to invest in base load and flexible load plants. It is apparent that the flexible load plant is more sensitive to price uncertainty of CO_2 quotas, with a positive EVW apparent above 30% CO_2 quota price volatility. That means that above a 5 year quota price volatility of 30%, the plant owner would choose to wait for more information before investing in CCS. In comparison, the EVW for a constant emissions plant becomes positive above 40% quota price volatility. Our model thus indicates that a base load plant owner could tolerate a higher level of CO_2 quota price volatility and still invest in CCS technology. With a flexible load plant however, a lower quota price volatility triggers a decision to wait. Accordingly, in the wake of substantial policy and CO_2 quota price uncertainty, base load capacity plants may be more attractive investments for CCS technology. Even more so because mitigating emissions for a base load power plant is always cheaper. Figure 8b compares the NPV of costs for CO_2 mitigation between constant and variable emissions plants assuming no price volatility and 35 year economic life time. The difference in costs increases with CO_2 quota prices.

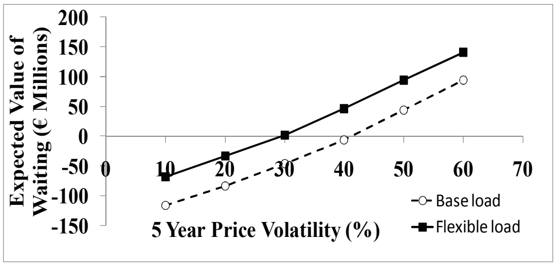

Figure 8a: Expected value of waiting for base load and flexible load plant investment scenarios at a range of CO_2 price volatilities.

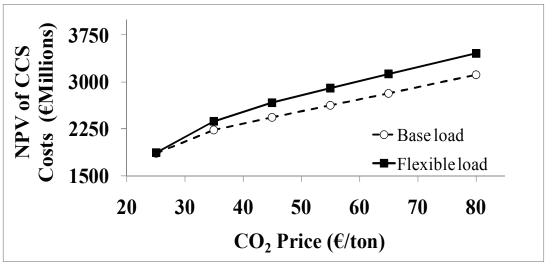

Figure 8b: Comparison of CCS Costs between base load and flexible load plants across a range of CO_2 prices.

The cost of mitigating CO_2 emissions for a flexible load plant, compared to a base load plant is € 132 million greater at a CO_2 quota price of € 35/ton and € 517 million at CO_2 quota price of € 80/ton. This increase is driven by emissions quota costs.

4. Conclusion

Economic factors affecting the choice of CCS chain capacity, and investment outcomes for CCS under base load and flexible load plant scenarios with volatile CO_2 quota prices, were discussed in this paper. We considered some of the economic variables influencing a plant's CCS chain capacity decision and found that the plant's emissions profile determined a range of capacities that could be efficient, with the optimal capacities resulting in greatest CCS capacity utilization to avoid excessive emissions quota payments and inefficiently high technology costs. The trade off between the price of CO_2 and the cost of CCS technology then determined which of the efficient CCS capacities would be optimal.

We then extended the decision tree investment model developed by Celebi and Graves [4] to include the additional selection of optimal CCS chain capacity at each price node on the investment decision tree. We found that with an emissions profile we used to simulate seasonal power production, it was generally not optimal to build CCS chain capacity equal to peak CO_2 flows, being more economical to pay for emissions quotas. As a result of the additional emissions quota payments, the expected cost of mitigating CO_2 emissions was greater for the flexible load plant than the base load plant, leaving the CCS investment decision in the flexible load power plant case more sensitive to price volatility.

Selecting a monthly time step for emissions in our analysis was a substantial simplification that influenced our results. Because of this coarse resolution, our flexible power generation case is more like a semi base load scenario. As a result, we may have overestimated the variable costs of flexible CCS plant operation by not accounting for efficiency gains on a daily time step from shutting off excess capacity. Higher variable costs may have resulted in lower optimal chain capacity estimates and contributed to greater susceptibility of the flexible load CCS plant to delay in investment from CO_2 quota price volatility. The implication of this is that industries with constant emission profiles or capture capacity limited to the constant load may be more attractive targets for initial investment into CCS, when future price uncertainty for CO_2 quotas may still be substantial.

Another important assumption in the analysis was that of constant, "locked in" CO_2 prices for the life of the CCS project. The effect of holding the price steady can be thought of as a subsidy or feed in tariff that reduces volatility and guarantees certain returns on the investment into CCS. This might be an attractive measure to support early CCS projects. On the other hand, because CO_2 prices do not increase over the project life, there is a limitation on returns from CO_2 price increases in the long run. This makes investment more sensitive to delay as a result of price volatility. Assuming an increasing price trajectory would decrease the effect of price volatility on the investment decision.

Additionally, we assume fixed electricity costs over the life of the CCS plant, while cost of electricity will likely increase in the coming decades. Including increasing electricity cost trajectories in the analysis would increase variable operating costs over time, driving up the price of CCS relative to the option of paying for emissions. If electricity costs rise relative to constant CO_2 quota prices, lower CCS chain capacities might become more economically efficient. In a more dynamic model, the rising cost of electricity relative to CO_2 quota price trajectories may be an important trade off in the decision of optimal CCS chain capacity.

Future work might utilize a more dynamic modelling approach to evaluate optimal CCS chain capacity under flexible power generation, incorporating high resolution plant emissions data, dynamic evolution of CO_2 quota and electricity prices. A real options analysis may provide a useful framework for this approach, and could be used to provide additional insights from considering CCS chain capacity selection under greenfield and retrofit plant scenarios, since retrofitting CCS results in efficiency losses.

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